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# Optimal Technology Selection and Operation of Commercial- Building Microgrids

*Chris Marnay, Giri Venkataramanan, Michael Stadler, Afzal Siddiqui, Ryan Firestone, and Bala Chandran*

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# Optimal Technology Selection and Operation of Commercial-Building Microgrids

C. Marnay, G. Venkataramanan, M. Stadler, A. S. Siddiqui, R. Firestone, and B. Chandran

**Abstract**—The deployment of small (< 1-2 MW) clusters of generators, heat and electrical storage, efficiency investments, and combined heat and power (CHP) applications (particularly involving heat-activated cooling) in commercial buildings promises significant benefits but poses many technical and financial challenges, both in system choice and its operation; if successful, such systems may be precursors to widespread microgrid deployment. The presented optimization approach to choosing such systems and their operating schedules uses Berkeley Lab's Distributed Energy Resources Customer Adoption Model (DER-CAM), extended to incorporate electrical and thermal storage options. DER-CAM chooses annual energy bill minimizing systems in a fully technology-neutral manner. An illustrative example for a hypothetical San Francisco hotel is reported. The chosen system includes one large reciprocating engine and an absorption chiller providing an estimated 11% cost savings and 8% carbon emission reductions under idealized circumstances.

**Index Terms**—buildings, building management systems, cogeneration, cooling, cost optimal control, dispersed storage and generation, distributed control, optimization methods, power system economics, power system planning

## I. INTRODUCTION

Herein, the working definition of a *microgrid* is: a cluster of electricity sources and (possibly controllable) loads in one or more locations that are connected to the traditional wider power system, or *macrogrid*, but which

may, as circumstances or economics dictate, disconnect from it and operate as an island, at least for short periods [1,2,3,4]. Note that the key distinguishing feature of a microgrid is local control, allowing it to operate as an island, thereby exercising control over the power quality and reliability (PQR) delivered to end-use devices.

The successful deployment of microgrids will depend heavily on the economics of distributed energy resources (DER), in general, and upon the early success of small clusters of mixed technology generation, possibly grouped with storage, controllable loads, and other potential microgrid elements. If clear economic, environmental, and utility system benefits from such early projects are realized, momentum can propel the adoption of added microgrid capabilities as well as precipitate the regulatory adjustments necessary to allow widespread microgrid introduction.

The potential benefits of microgrids are multi-faceted, but from the adopters' perspective, there are two major groupings: 1) the cost, efficiency, and environmental benefits (including possible emissions credits) of combined heat and power (CHP), and 2) the PQR benefits of on-site generation and control. Indeed, the economic, electrically stable, and safe operation and control of such free-standing, small-scale systems create new challenges for electrical engineers.

At the same time, it should be noted that growth in electricity demand in developed countries centers on the residential and commercial sectors in which CHP applications particularly (and PQR control to a lesser extent) have not hitherto been well developed; furthermore, the relative absence of attention to CHP and PQR reflects some real technical challenges posed by commercial and residential applications.

This paper reports on the latest in a series of efforts intended to improve the prospects for successful deployment of early microgrid technology in the commercial sector [5], and the approach could be applied also to residences. In previous work, the Berkeley Lab has developed the Distributed Energy Resources Customer Adoption Model (DER-CAM), which is described in more detail in the appendix [6,7,8]. Optimization techniques find both the combination of equipment and its operation over a typical year that minimize the site's total energy bill, typically for electricity plus natural gas. The chosen equipment and its schedule should be economically attractive to a single site or to members of a microgrid consisting of a cluster of sites, and it should be subsequently analyzed in more engineering and financial detail. In this work, electrical and thermal storage is added as an option to the prior menu of technology choices,

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Chris Marnay is a Staff Scientist with the Ernest Orlando Lawrence Berkeley National Laboratory (Berkeley Lab), Berkeley, CA 94720-8136, U.S.A. (e-mail: [C\\_Marnay@lbl.gov](mailto:C_Marnay@lbl.gov)).

Giri Venkataramanan is an Associate Professor at the University of Wisconsin-Madison (e-mail: [giri@engr.wisc.edu](mailto:giri@engr.wisc.edu)).

Michael Stadler is with the Center for Energy and Innovative Technologies, Austria and a Visiting Scholar at Berkeley Lab ([MStadler@lbl.gov](mailto:MStadler@lbl.gov)).

Afzal Siddiqui is with the Department of Statistical Science at University College London (e-mail: [afzal@stats.ucl.ac.uk](mailto:afzal@stats.ucl.ac.uk)).

Ryan Firestone was a Graduate Student Research Assistant with Berkeley Lab, and is now with Summit Blue Consulting, LLC (e-mail: [ryan.firestone@gmail.com](mailto:ryan.firestone@gmail.com)).

Bala Chandran was a Graduate Student Research Assistant with Berkeley Lab, and is now with Analytics Operations Engineering, Inc. (e-mail: [bgchandran@gmail.com](mailto:bgchandran@gmail.com)).

and this capability is demonstrated by the analysis of a prototypical San Francisco hotel.

## II. DER IN BUILDINGS

The importance of the commercial sector in electricity consumption in developed countries can be seen by three multiplicative factors. 1. The share of all energy being consumed as electricity increases, e.g. in the U.S. from 13% in 1980 to about 20% today. 2. The commercial sector uses a growing share of all electricity, e.g. in the U.S. from 27% in 1990 to 35% in 2005. And 3., typically an increasing share of electricity is generated thermally as carbon-free hydro sources are fully exhausted, although the shares of carbon-free nuclear vary widely across grids. The product of these factors means the carbon footprint of commercial buildings can grow rapidly, but changes in the fuel mix, e.g. more natural gas fired generation, can also have a big effect. Further, in warm climates such as most of the U.S. and Japan, and for an increasing share of Europe, commercial-sector cooling is a key driver of peak load growth, and hence, the stress to and investment in the macrogrid. Consequently, deployment of DER in buildings, especially CHP technologies for cooling, is central to containing the growth of electricity consumption and its associated carbon emissions.

Yet, despite the importance of DER in the commercial sector, current analysis of DER implementation in buildings is limited. System sizing often relies on heuristic rules based on the relative size of heat and electricity requirements. Furthermore, the detailed building energy modeling that is frequently done during building design to assist in the selection of energy systems relies on quite limited programs [9]. Their on-site generation capability is often limited to modeling a few generation sources, such as photovoltaic panels (PV), and possibly some heat recovery devices. And, typically, the usefulness of the analysis rests heavily on user capability and motivation. Although DER can offer a variety of economic, environmental, and remote macrogrid benefits, such as enhanced demand response, the lack of DER assessment tools is a major hurdle to widespread DER adoption. Developers are lacking the ability to assess the cost, energy use, and carbon and criteria pollutant implications of DER options, and their ability to identify optimal equipment combinations and operating strategies is limited at best. This gap is particularly damaging for DER incorporating CHP because equipment selection and operations can be complex in building applications, often involving multiple technologies, combinations of electricity purchase and self-generation, and highly varied scheduling to follow the occupancy, weather, and other variations in building requirements. Consequently, DER with CHP is rarely explored for buildings too small to justify specialized engineering, e.g. with peak electrical loads approximately below the 1-2 MW range, and particularly waste heat driven cooling is rarely analyzed, despite the importance of cooling to both building requirements and utility system loads in warm climates.

Electrical and/or thermal storage technologies that allow desynchronization of electricity generation and heat use in building CHP systems are potentially cost effective. They permit charging and discharging during periods when each is economic, which is obviously potentially beneficial. More subtly, storage allows decoupling of the electricity and heat balances, with the latter being much more forgiving. For example, deviations from target building temperature settings for periods of minutes to hours may be acceptable (or at least negotiable, given potential cost savings), whereas practically speaking, AC electrical systems require a precise energy balance at all times. This asymmetry, while it offers potential financial motivation, further complicates analysis of building CHP systems. Only active storage systems are considered in this work, but passive storage, e.g. heat storage in the building shell itself, might also provide benefits. Note the contrast between building CHP applications with traditional (principally industrial) experience. The latter are typically applications with favorable balances of heat and electricity requirements, and processes operate in a steady state for extended periods (preferably from an economic perspective, 24/7).

## III. DER-CAM

DER-CAM solves the commercial building DER investment optimization problem given a building's end-use energy loads, energy tariff structures and fuel prices, and an arbitrary list of equipment investment options [10]. The approach is fully technology-neutral and can include energy purchases, on-site conversion, both electrical and thermal on-site renewable harvesting, and end-use efficiency investments. Furthermore, the system choice considers the simultaneity of the building cooling problem; that is, results reflect the benefit of displacement of electricity demand by heat-activated cooling that lowers building peak load and, therefore, the generation requirement. Regulatory, engineering, and investment constraints are all considered. Energy costs are calculated using a detailed representation of utility tariff structures and fuel prices as well as amortized DER investment costs and operating and maintenance (O&M) expenditures. For a specific site, the source of end-use energy load estimates is typically building energy simulation using a model based on the DOE-2 engine, such as eQUEST, or the more advanced, but less user-friendly, EnergyPlus [11,12].

The output from DER-CAM is a cost-minimizing equipment combination for the building, including CHP equipment and renewable sources. The model chooses the optimal combination, fully taking the simultaneity of choices into account. The results of DER-CAM suggest not only an optimal (potentially mixed technology) microgrid, but also an optimal operating schedule that can serve as the basis for a microgrid control strategy; however, the rigors of optimization necessitate simplification of many real-world engineering constraints that would in practice necessarily be addressed through more detailed engineering analysis and system design.

Optimal combinations of equipment involving PV, thermal generation with heat recovery, thermal heat collection, and heat-activated cooling can be identified in a way that would be intractable by trial-and-error enumeration of possible combinations. The economics of storage are particularly complex, both because they require optimization across multiple time steps and because of the influence of tariff structures. Note that facilities with on-site generation will incur electricity bills more biased toward demand (peak power) charges and less toward energy charges, thereby making the timing and control of chargeable peaks of particular operational importance. Similarly, if incentive tariffs that share the macrogrid benefits of DER with the microgrid are available, then the operational problem is further complicated because identifying any potential contribution to the macrogrid would likely be intractable without optimizing algorithms.

This paper reports results using recently added electrical storage, i.e. a conventional lead/acid battery, and thermal capabilities, with both electrical and thermal storage being viewed as inventories. At each hour, energy can either be added (up to the maximum capacity) or withdrawn (down to a minimum capacity to avoid damaging deep discharge). The rate at which the state of charge can change is constrained, and the state of charge decays hourly. The parameters used for the electrical and thermal storage models are shown in the following Table 1, where perfect efficiency is assumed in the discharge phase.

TABLE 1  
ENERGY STORAGE PARAMETERS

	description	electrical	thermal
<b>charging efficiency</b>	portion of energy input to storage that is useful	0.9	0.9
<b>decay</b>	portion of state of charge lost per hour	0.001	0.01
<b>maximum charge rate</b>	maximum portion of rated capacity that can be added to storage in an hour	0.25	0.25
<b>maximum discharge rate</b>	maximum portion of rated capacity that can be withdrawn from storage in an hour	0.25	0.25
<b>minimum state of charge</b>	minimum state of charge as a portion of rated capacity	0.3	0

#### IV. SAN FRANCISCO HOTEL EXAMPLE

An example analysis was completed of a prototypical San Francisco hotel operating in 2004. This hypothetical facility has 23 000 m<sup>2</sup> of floor space and a peak total electrical load of 690 kW. Figures 1 through 4 indicate heating and electricity end-uses during typical January and July week days. Table 2 shows the prices used, which are based on

local Pacific Gas and Electric (PG&E) rates obtained from the Tariff Analysis Projects database [13]. Here, the summer months are June through September, inclusive, and the hours are classified as follows: during the summer, 1000-1900 are on-peak during week and peak days, and the rest are off-peak, while during the winter, 0900-2200 are on-peak and the rest are off-peak. All hours during holidays and weekend days are off-peak hours. Natural gas prices (shown in two units) for the region were obtained from the Energy Information Administration web site [14]. A marginal carbon emission factor of 140 g/kWh for electricity purchased from PG&E was assumed, whereas the efficiency of macrogrid electricity generation was assumed to be 0.34 [15]. The solar insolation profile for the solar thermal unit is indicated in Figure 5, which is a fraction of the theoretical maximum that the PV panel could output under test conditions.

The menu of available equipment options to DER-CAM for this analysis together with their cost and performance characteristics is shown in Table 3. While the current set of technologies is for convenience, any candidate technology may be included. Technology options in DER-CAM are categorized as either *discretely* or *continuously* sized. This distinction is important to the economics of DER because equipment becomes more expensive in small sizes. Discretely sized technologies are those that would be available to customers only in a limited number of discrete sizes, and DER-CAM must choose an integer number of units, e.g. microturbines. The costs for the discrete technologies are interpolated from various studies as described in [16], which is based on data collected by the National Renewable Energy Laboratory [17]. Continuously sized technologies are available in such a large variety of sizes that it can be assumed capacity close to the optimal could be acquired, e.g. battery storage, the costs for which are roughly consistent with those described by the Electricity Storage Association [18]. The installation cost functions for these technologies are assumed to consist of an unavoidable cost (intercept) independent of installed capacity (\$) representing the fixed cost of the infrastructure required to adopt such a device, plus a variable cost proportional to capacity (\$/kWh). Finally, the carbon emission factor for each DG unit is calculated by dividing the natural gas emission factor of 49 g/kWh by the appropriate higher heating value (HHV) efficiency. For example, the carbon emission factors are 197 g/kWh and 187 g/kWh for the 60 kW and 100 kW microturbines, respectively, and 167 g/kWh and 166 g/kWh for the 200 kW and 500 kW reciprocating engines, respectively.

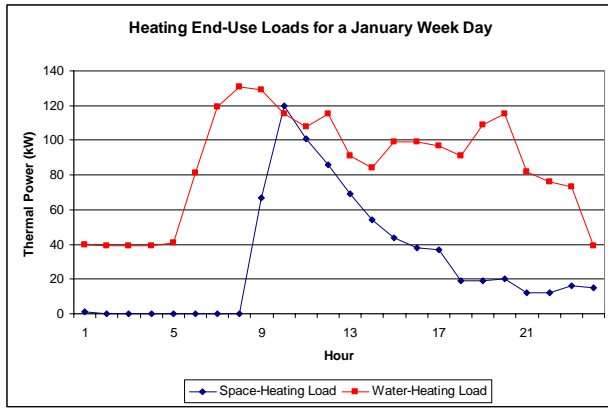


Fig. 1. Heating end-use loads for a January week day

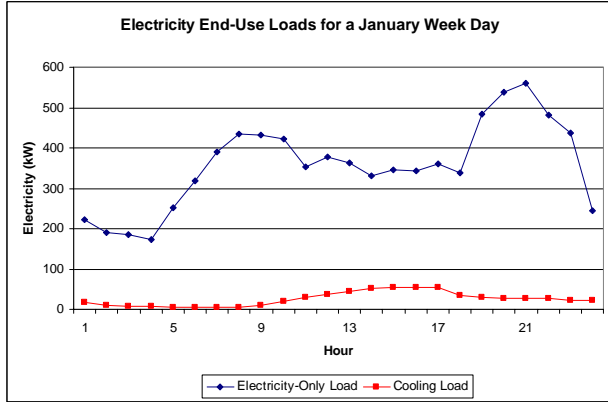


Fig. 2. Electricity end-use loads for a January week day

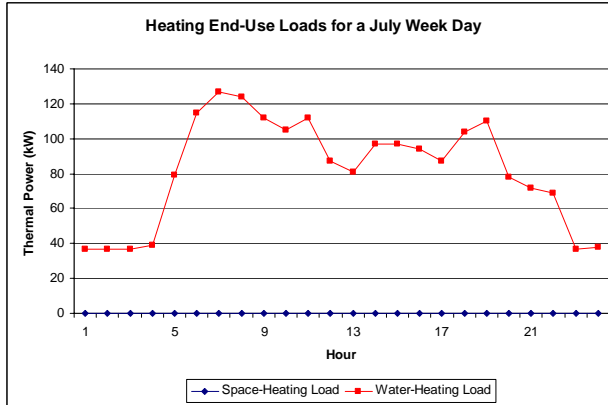


Fig. 3. Heating end-use loads for a July week day

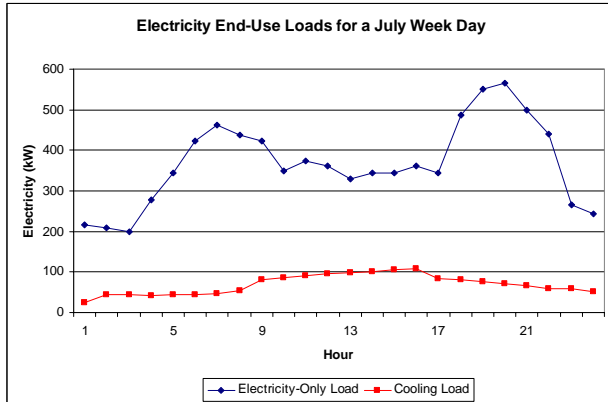


Fig. 4. Electricity end-use loads for a July week day

TABLE 2  
INPUT ENERGY PRICES**Electricity**

	summer		winter	
	electricity (\$/kWh)	demand (\$/kW)	electricity (\$/kWh)	demand (\$/kW)
all hours		2.55		2.55
on-peak	0.17	11.80	0.11	0.00
off-peak	0.09	0.00	0.09	0.00

**Natural Gas**

0.03 \$/kWh
0.94 \$/therm

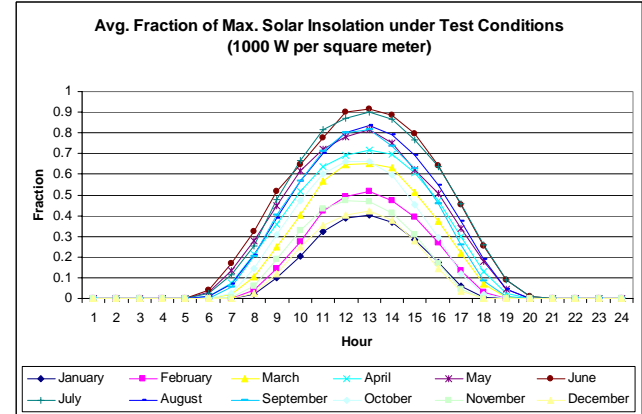


Fig. 5. Solar insolation profile

TABLE 3  
MENU OF AVAILABLE EQUIPMENT OPTIONS**Discrete Investments**

	fuel cell	microturbine		reciprocating engine	
capacity (kW)	200	60	100	200	500
installed cost (\$/kW)	5005	1826	1576	900	785
installed cost with heat recovery (\$/kW)	5200	2082	1769	1250	1050
variable maintenance (\$/kWh)	0.029	0.015	0.015	0.015	0.012
efficiency (LHV)	0.35	0.25	0.26	0.295	0.297
lifetime (a)	10	10	10	20	20

**Continuous Investments**

	electrical storage	thermal storage	absorption chiller	solar thermal	photovoltaics
fixed cost (\$)	295	10,000	20,000	1,000	1,000
variable cost (\$/kW or \$/kWh)	193	100	115	150	4,240



From the data, DER is not necessarily more energy or carbon efficient than central station generated power bought from the grid. For example, simple cycle on-site generation of electricity using reciprocating engines at this site would be more carbon intensive than procurement from PG&E; however, using waste heat to offset thermal or electrical loads can improve the overall carbon efficiency. Because incentive payments are usually motivated by efficiency or carbon abatement objectives, qualifying constraints on minimum DER efficiency are often imposed. Although California has these, they are not applied in this analysis.

TABLE 4  
ANNUAL RESULTS

	do nothing	invest	low storage price	force low storage price
<b>equipment investment</b>				
reciprocating engines (kW)		1x500	1x200	1x200
absorption chiller (kW)		531	585	585
solar thermal collector (kW)			642	642
electrical storage (kWh)			763	
thermal storage (kWh)			176	
<b>annual costs (k\$)</b>				
electricity	427	100	202	228
NG	33	229	136	127
DG	0	78	62	52
total	459	408	400	407
% savings		11.2%	12.8%	11.3%
<b>annual energy consumption (GWh)</b>				
electricity	3.67	0.95	1.87	1.98
NG	0.98	7.85	4.65	4.33
<b>annual carbon emissions (t/a)</b>				
emissions	562	520	491	492
% savings		7.4%	12.7%	12.6%
<b>system energy efficiency</b>				
efficiency	0.38	0.42	0.44	0.44

## V. RESULTS

Four DER-CAM runs were performed: 1. A *do nothing* case in which all DER investment is disallowed, i.e. the hotel meets its local energy demands via off-site purchases. 2. An *invest* run, which finds the optimal DER investment. 3. A *low storage price* run by reducing the cost to initiate storage adoption. 4. Finally, to assess the value of storage systems, a run was performed forcing the same investments as in the low storage price case, but in which storage is disallowed.

The major results for these four runs are shown in Table 4. In the *do nothing* case, the hotel meets all of its electricity demand via utility purchases and burns natural gas to meet all of its heating demand at an overall system energy efficiency

of 0.38. The annual operating cost is \$459 000, and 562 t of carbon are emitted each year. The optimal system consists of a large gas engine and an absorption chiller. Relative to the *do nothing* case, the expected annual savings for the optimal DER system are \$51 000/a (11.2%) and the elemental carbon emissions reduction is 42 t/a (7.5%). By running DER-CAM for various load data, tariff structures, and candidate technologies, it is possible for a microgrid to construct an optimal DER investment plan. For example, we ran three cases, each with a slightly different optimal portfolio of equipment.

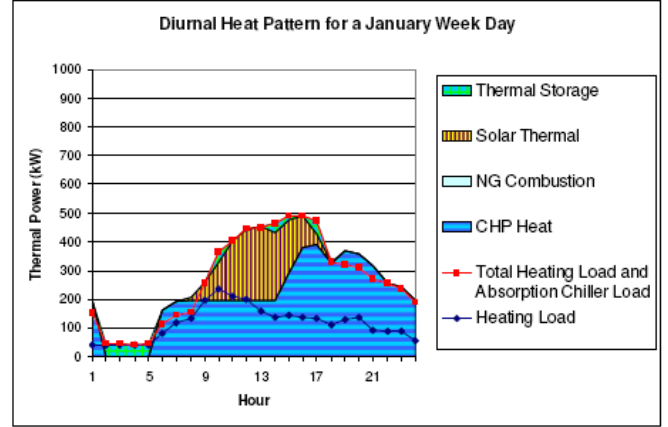


Fig. 6. Low storage price diurnal heat pattern for a January week day

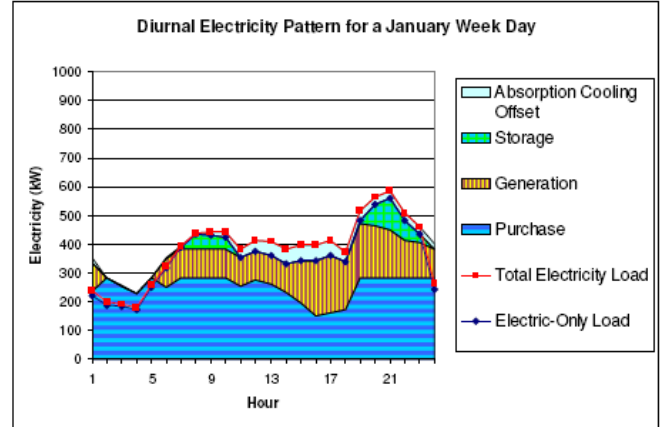


Fig. 7. Low storage price diurnal electricity pattern for a January week day

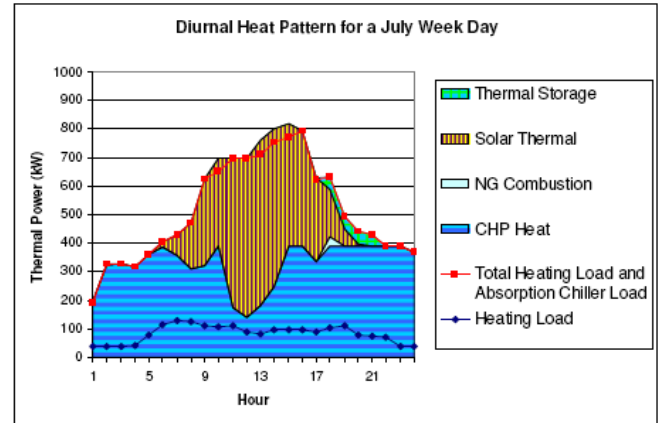


Fig. 8. Low storage price diurnal heat pattern for a July week day

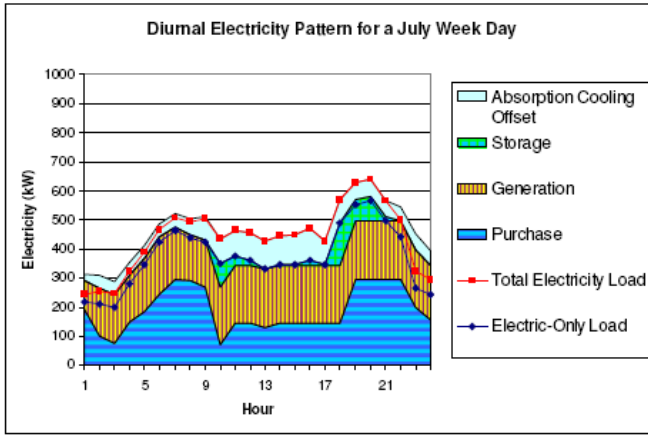


Fig. 9. Low storage price diurnal electricity pattern for a July week day

In the *low storage price* case, both avoidable electrical and thermal storage costs are set to zero plus a \$40/kWh variable cost. Compared to the *invest* case, a more complex DER system results in which some generation capacity is replaced by storage and solar thermal collection, but the annual costs are reduced to 12.8% below the *do nothing* case, which is a small improvement relative to the *invest* case. In other words, the added value of the storage and other complexity is very modest in this example. An explanation for this is that storage can take advantage of both economic and temporal inefficiencies, i.e. by charging the battery via utility purchases during off-peak hours and then consuming the stored power during on-peak hours. However, since the latter are small relative to the cost of storage (even in the *low storage price* case), the additional cost savings are not very high beyond those that are already captured by the CHP-enabled generator, which is also able to run during on-peak hours to offset the cooling electric load via the absorption chiller. Nevertheless, the impact on carbon emissions is greater as they are reduced by 12.7% in the *low storage price* case as compared to only 7.5% in the *invest* case. In order to estimate a value for storage, we perform a run with low storage prices, but no storage allowed (*force low storage price*) while a solar thermal unit is still permitted. We find that the presence of storage increases savings to 12.8% whereas they are 11.3% without it.

There is a large difference between the DER systems in the last three cases and yet only minor difference in their energy cost, which suggests a flat objective function near the minimum. It is also likely that results would be sensitive to factors not considered in this analysis, such as risk and site configuration. Please also note that these results are estimated assuming perfect reliability of DER equipment. Imperfect reliability would mostly directly affect the demand charges, but would also have other effects on the value of the project to the site, e.g. on the standby charge as back up to DER would have to be provided by the utility.

Besides the optimal investment plan, DER-CAM provides the microgrid with an optimal schedule for each installed technology, which we illustrate using the *low storage price* case. The graphics in Figures 6 through 9 above show

example DER-CAM operating results for the thermal and electrical balances of the hotel on typical days in January and July 2004. Note that the optimal technologies are a 200 kW reciprocating engine, a 585 kW (166 refrigeration tons) absorption chiller, 642 kW of solar thermal collectors, 763 kWh of electrical storage, and 176 kWh of thermal storage. While the economics of this case are not compelling, even with subsidized storage, it is presented in detail to demonstrate the scheduling capability of DER-CAM.

The area underneath the solid red line in these figures is the hourly energy demand, whereas the area above the solid red line indicates storage charging. The various patterns in the graphs indicate the source of the energy. For electrical loads (Figures 7 and 9) the lower black profile indicates the portion of the electric load that can be met by only electricity, whereas the solid red line above it is the total electric load, including cooling. During off-peak hours, the microgrid purchases cheap power from the utility to charge the battery and then consumes the stored power during on-peak periods when utility purchases are relatively expensive. Note that since electric cooling loads can be offset by the absorption chiller, there are four possible ways to meet cooling loads: utility purchases of electricity, on-site generation of electricity, absorption chiller offsets, and stored electricity in batteries. By finding the optimal combination for each hour of the test year, DER-CAM provides the microgrid with an optimal operating schedule for each of its installed technologies. For thermal loads (Figure 6 and 8), the lower line indicates the heat required for heating, whereas the solid red line indicates the total thermal load, including heat required for the absorption chiller.

## VI. CONCLUSIONS

Limiting the growth of electricity consumption in commercial buildings is particularly important for carbon abatement in developed countries. Unfortunately, the promising approach of deploying CHP (especially cooling) technology faces major challenges. Use of better building energy analysis and design tools can accelerate the adoption of CHP, and thus facilitate deployment of microgrids nationally that can additionally deliver PQR benefits [19]. Both thermal and electrical storage capability have been added to DER-CAM, thereby making it a more useful optimization tool for on-site generation selection and operation. The new capabilities have been demonstrated by an analysis of a prototypical San Francisco hotel. Results show the wide range in complexity of optimal systems and the likely carbon emissions reductions. It should be noted that although the example demonstrated herein has primarily focused on the optimal choice of investments, optimization of run-time operational schedules are implicit in the method, and examples are reported as figures.

Incorporation of electrical storage into DER-CAM will facilitate analysis of emerging transportation technologies. For example, the adoption of plug-in hybrids as personal transportation, with their on-board electrical storage offer an



on-site load leveling opportunity at minimal additional investment with potential for additional reduction in carbon emissions. Note that payments for the storage capability of vehicles, as well as for other possible services, such as rapid-response load following, could make the economics of such transportation modes more favorable and accelerate their deployment. The integration of such features into DER-CAM is a promising topic for further investigations.

## VII. APPENDIX

DER-CAM identifies optimal technology-neutral DER investments and operating schedules at a given site based on available DER equipment options and their associated capital and O&M costs, customer load profiles, energy tariff structures, and fuel prices. The Sankey diagram in Figure A1 shows partially disaggregated site end-uses on the right-hand side and energy inputs on the left. As an example, the refrigeration and cooling load may be met in one of multiple ways, including standard electrically powered compressor cooling, direct fire or waste heat activated cooling, or direct gas engine powered compressor cooling (not included in the hotel example analysis above). DER-CAM solves this entire problem optimally and systemically. Figure A2 shows a high level schematic of inputs to and outputs from the model.

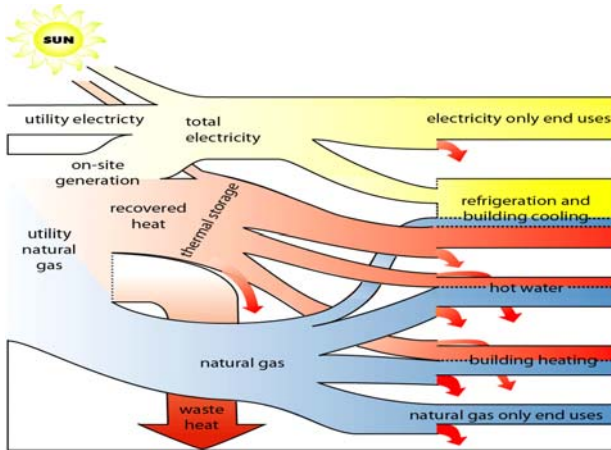


Fig. A1. Energy flows in buildings from fuels to end uses

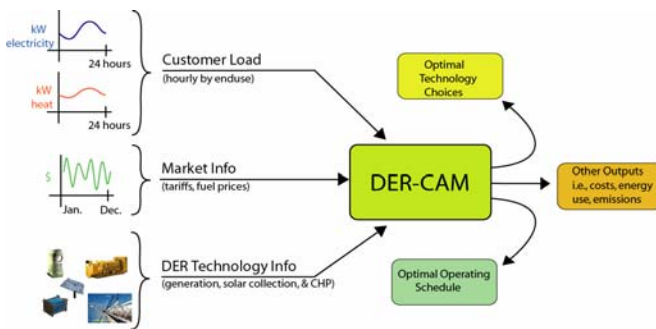


Fig. A2. High level schematic of the inputs and outputs of DER-CAM

DER-CAM is particularly suited to evaluating combined heat and power (CHP) opportunities since it selects the optimal combination of DER investment options, fully taking

their interdependence into account, e.g. if there is a tradeoff between thermally activated cooling and on-site generator capacity, DER-CAM obtains the combination of the two that minimizes cost. Thus, optimal combinations of equipment involving PV, thermal generation with heat recovery, solar thermal collection, and thermally activated cooling can be identified in a way that would be intractable by trial-and-error testing of all possible combinations.

DER-CAM is implemented as a mixed-integer linear program in the General Algebraic Modeling System (GAMS) using the CPLEX solver. A high level description of the model logic is shown in Figure A3. Siddiqui et al. provides a more detailed description [8].

```

MINIMIZE
  Annual energy cost:
    energy purchase cost
    + amortized DER technology capital cost
    + annual O&M cost

SUBJECT TO
  Energy balance:
    - Energy purchased + energy generated exceeds demand
  Operational constraints:
    - Generators, chillers, etc. must operate within
      installed limits
    - Heat recovered is limited by generated waste heat
  Regulatory constraints:
    - Minimum efficiency requirements
    - Maximum emission limits
  Investment constraints:
    - Payback period is constrained
  Storage constraints:
    - Electricity stored is limited by battery size
    - Heat storage is limited by reservoir size

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Fig. A3. Optimization problem solved by DER-CAM

## VIII. ACKNOWLEDGMENT

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## X. BIOGRAPHIES



**Bala Chandran** holds a Ph.D. from the Department of Industrial Engineering and Operations Research at the University of California, Berkeley, a B.Tech. in Civil Engineering from the Indian Institute of Technology, Madras, and an M.S. in Business and Management from the University of Maryland. He currently works with the Analytics Operations Engineering, Inc., Boston, MA. His research interests are in large-scale optimization and modeling.



**Ryan Firestone** earned a Ph.D. at the University of California, Berkeley, a Sc.B. degree from Brown University, and an M.S. degree from the University of Texas El Paso in 2001, all in mechanical engineering. His doctoral research explored the optimal dispatch of DER in stochastic systems. He was a Graduate Student Research Assistant with Berkeley Lab until June 2007 and is now with Summit Blue Consulting, Walnut Creek, CA.



**Chris Marnay** is a Staff Scientist in the Energy Environmental Technologies Division of Berkeley Lab. He specializes in problems concerning likely future adoption patterns of small scale DER, especially those involving commercial building use of heat activated cooling, and renewables. He has an A.B. in Development Studies, an M.S. in Agricultural and Resource Economics, and a Ph.D. in Energy and Resources, all from the University of California, Berkeley.



**Afzal Siddiqui** is a Lecturer in the Department of Statistical Science at University College London. His research interests lie in investment and operational analysis of electricity markets. In particular, he focuses on distributed generation investment under uncertainty, optimal scheduling of distributed generation, real options analysis of renewable energy technologies, and demand response. He holds the following degrees in industrial engineering and operations research: a B.S. from Columbia University, New York, an M.S. and a Ph.D. from the University of California, Berkeley.



**Michael Stadler** joined Berkeley Lab as a student in 2002, returned as Post-Doctoral Fellow in 2005, and is currently a Visiting Scholar. He also supported the University of California, Berkeley's Pacific Region CHP Application Center, where he conducted site analyses of varied commercial, agricultural, and industrial CHP projects. Previously, he worked with the Energy Economics Group at the Vienna University of Technology, from which he holds a Masters degree in electrical engineering and a Ph.D. *summa cum laude* in energy economics. His fields of research are distributed energy, electricity markets, and demand response.



**Giri Venkataramanan** (M'92) received a B.E. in electrical engineering from the Government College of Technology, Coimbatore, India, an M.S. from the California Institute of Technology, Pasadena, and a Ph.D. from the University of Wisconsin, Madison in 1986, 1987 and 1992 respectively. After teaching at Montana State University, Bozeman, he returned to Madison as a faculty member in 1999, where his research continues in various areas of electronic power conversion. He serves as Associate Director of the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC). He holds six U.S. patents and has coauthored more than a hundred technical publications.